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The beginning of cosmic ray astrophysics

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Abstract

A short history of the beginning of cosmic ray (CR) astrophysics is considered: from the hypothesis on CR origin as a result of Supernova explosions in the Metagalaxy, to a model of solar origin of CR, galactic origin based on the stochastic mechanism of charged particle acceleration in interstellar space, to extragalactic and hierarchical models of CR origin, as well as galactic CR origin taking into account radio-astronomical data. We consider also the first balloon results on the chemical contents of primary CR (especially of the contents Li, Be, B), important for any model of CR origin. Investigations of the injection problem, CR drift and diffusion acceleration by shock waves, and CR generation in Supernova remnants were also important steps in the beginning of CR astrophysics.

Keywords: Cosmic rays; Models of origin; Acceleration mechanisms; Connection with radio and gamma astronomy; Supernova explosions and remnants as main sources

1. Supernova explosions in the Metagalaxy as main sources of CR

As we underlined in Dorman (M1957), the interest in research of CR variations in sidereal time sharply increased after Baade and Zwicky (1934a,b) hypothesized that the basic sources of CR are most likely such grandiose processes with huge allocation of energy as Supernova explosions (in Fig. 1 is shown one of authors of this idea).

Baade and Zwicky based these papers on CR intensity measurements, which showed in that time that there are no CR time variations and that the CR intensity from all directions is about the same. From this, they concluded that the main sources of CR are not in the Milky Way, but rather in the Metagalaxy. As Baade and Zwicky estimated (1934a), the frequency of Supernova explosions in the Metagalaxy is about one in one thousand years in the cube whose edge is $L = 10^6$ light years. During the lifetime of a Supernova, the intensity of total radiation (visible and invisible) is estimated to be about 3.8×10^{48} erg/s. During its life, a Supernova emits at least $10^5\,\text{s} \times 3.8 \times 10^{48}$ erg/s $= 3.8 \times 10^{53}$ erg. If it is supposed that the majority of the energy is going towards CR generation, the expected intensity will be about 2×10^{-3} erg/(s cm^2), which is comparable with the CR intensity of about 3×10^{-3} erg/(s cm^2) observed in that time.

Let us note that the estimation by Baade and Zwicky of Supernova energy going towards the generation of CR is overestimated by about two orders. In reality, for CR generation and acceleration, only mechanical energy of moving plasma with frozen-in magnetic fields, which is about hundred times smaller than the total energy of a Supernova explosion, goes toward CR. The second note is about the opinion of Baade and Zwicky that CR cannot be generated in our Galaxy (this opinion was based on the absence of CR stellar anisotropy and the absence of big CR intensity variations with stellar time). In reality, according to present knowledge about primary CR chemical and isotopic contents, the average time of life of CR in our Galaxy is about 3×10^7 years. In this amount of time, there will be at least about 10^5 Supernova explosions in our Galaxy. This means

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Fig. 1. Fritz Zwicky (1898–1974).

that CR that we observe now are the result of many very big Supernova explosions, and the explosion of one of them will negligibly change the CR intensity. Only in very rare cases, when the Supernova explosion is not far from the Sun (the distance smaller than 30–100 pc), can the time variations of CR intensity and stellar CR anisotropy be expected to be significant. The third note is about the supposition of Baade and Zwicky that observed CR have extragalactic origin, i.e. that the intensity of CR in intergalactic space is the same as near the Earth. As it was shown in Section 5, in this case, the total energy in CR should be too high. This huge value of total energy in CR seems absolutely unrealistic. Nevertheless, the idea of Baade and Zwicky of Supernovae as the main sources of CR became very fruitful, and was accepted and developed later by many scientists (e.g., Ginzburg and Syrovatsky, 1963; Berezhko et al., 1988; Berezinsky et al., 1990).

2. Hypothesis on the solar origin of CR

As it was well known, after 1942 there were observed several short time periods when the Sun generated CR up to energies of 10–30 GeV. This circumstance, and also the failure in the search for a stellar-daily variation, led a number of researchers to begin to abandon the idea of a solar origin of cosmic radiation. Also, it was promoted by detection of a solar-daily variation with a maximum near the local solar time 12^h, i.e. due to the additional CR flux from the Sun (however, as it was shown later in Dorman, M1957, this argument is not correct: when by the method of coupling functions the effective energy of CR solar-daily variation was determined, and then the correction on the influence of the geomagnetic field on the trajectories of CR particles was made, the maximum of CR solar-daily variation out of the Earth's magnetosphere became about 18^h, i.e. perpendicular to the direction to the Sun. Moreover, as it was shown later by Krymsky (1964), this perpendicular direction of CR solar-daily variation is caused by the diffusion propagation of CR into interplanetary space with an Archimedean spiral magnetic field from outside the Solar system). In particular, Rihtmyer and Teller (1948) stated the idea that CR basically are generated on the Sun and are kept by magnetic fields in interplanetary space. Detailed development of the hypothesis of a solar origin of CR is given in Alfvén's papers (1949, 1950), see Fig. 2.

H. Alfvén was against both extragalactic and galactic CR hypotheses. He estimated that in both cases, it is necessary to ascribe to CR very high energy, which in his opinion is not possible. H. Alfvén concluded that CR observed on the Earth must be of local origin, and concentrated not far from the Sun: protons should be accelerated in interplanetary space up to energies equal to 5×10^{13} eV. However, the hypothesis of solar origin of the basic part of CR met with serious difficulties. It was impossible to explain acceleration of particles to higher energies, while by means of installations of extensive atmospheric showers it was shown that there are particles in CR with energies of more than 10^{17}–10^{18} eV. Apparently, the definitive blow to the CR solar origin hypothesis was struck by radio-astronomical measurements of nonthermal radio emission of the Galaxy, which directly showed the presence of high-energy electrons in interstellar space, synchrotron radiated in extended magnetic fields (Ginzburg, 1948; see review in Ginzburg and Syrovatsky, 1963; Berezinsky et al., M1990). Later, the final blow to this hypothesis was struck by measurements of γ-rays from π^0-decay generated in Supernova remnants and in interstellar space by nuclear interactions of CR high-energy protons, α-particles, and heavier nuclei with plasma matter: TeV-emission from a restricted number of nearby SNRs (from SN1006, Cas A, RXJ 1713, Vela's and Tycho's SNR) and extra-galactic sources was measured by ground based Cherenkov telescopes HEGRA, HESS, Magic, Veritas (e.g., Albert et al., 2007; Torres et al., 2008; Acciari et al., 2008, 2010; De Angelis, 2013) and GeV-emission from some galactic

Fig. 2. Hannes Alfvén (1908–1995) – Nobel Laureate in Physics.